MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MV-66-2

BIOPHYSICAL EVALUATION OF THE HUMAN VESTIBULAR SYSTEM

Principal Investigators: J.L. Meiry
L.R. Young

June 1966

First Semi-Annual Status Report
on NASA Grant NGR 22-009-156

MAN-VEHICLE CONTROL LABORATORY
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ABSTRACT

The physical properties of the vestibular system and its fluids are investigated to determine an analytical model of the system. The theoretical response of the semicircular canals to caloric stimulation, angular rotation and linear acceleration is evaluated and compared to existing experimental data. Progress in experimentation with the labyrinthine fluids and in modeling of the semicircular canals is reported.

by Principal Investigators: J. L. Meiry
L. R. Young

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II. INTRODUCTION

The Man-Vehicle Control Laboratory performs research in a number of areas relating to the limitations and capabilities of men involved in the guidance, control and stabilization of moving vehicles. Our approach stresses the application of automatic control theory to an interdisciplinary field which includes problems in psychology and biology as well as control systems. The design of experiments and analysis of results leans heavily on the concepts of analytic or semi-analytic models of human characteristics.

In this program, we seek to advance the overall Man-Vehicle Control Laboratory objectives of extending the quantitative description of the human vestibular sensors. By a detailed investigation of the structural and physical properties of the nonauditory labyrinth and its fluids we hope to identify the source of several experimentally observed phenomena and to present a useful mathematical model for future biophysical and engineering application.

The orientation of the various parts of this research may be seen by reference to Figure 1. The semicircular canals are viewed as angular motion sensors whose physical parameters can be described by the fluid dynamics analysis

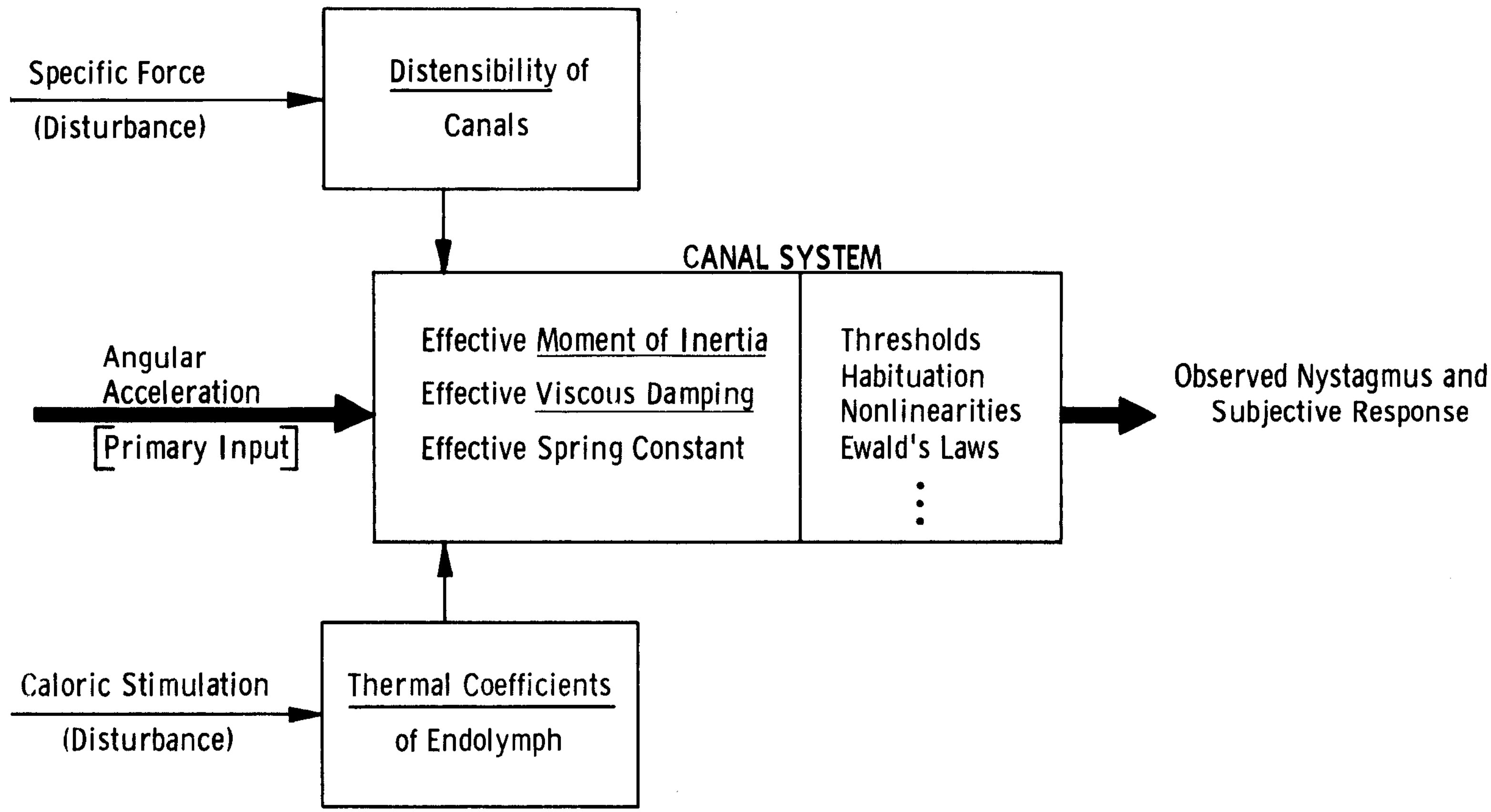

Fig. 1 Semicircular canal viewed as a physical instrument.

of a rotating torus. The observable "outputs" of the sensor and CNS processing are subjective sensations of rotation and nystagmoid eye motion. Inputs other than rotation which affect the canal's operation may be viewed as disturbances. Two of these disturbances, caloric stimulation and specific force (linear acceleration and gravity) are shown schematically as affecting the canal through its thermal coefficients and distensibility.

Three areas of interest were singled out for concentrated effort during the first half of 1966 as indicated by the items underlined in Figure 1. The following sections of this report will touch briefly on the research carried out in each of these areas; physical properties of the labyrinthine fluids, fluid dynamics analysis of the cupular-endolymph system and caloric stimulation of the semicircular canals. Mr. Robert Steer, a doctoral candidate in Instrumentation, is actively participating in this program.

III. PHYSICAL PROPERTIES OF THE LABYRINTHINE FLUIDS

One of the primary goals of the research carried out under the subject grant is to effect a unified description, theoretical and experimental, of the vestibular apparatus. To further this goal, a detailed knowledge of the physical properties of the labyrinthine fluids is necessary and essential. The chemical properties of these fluids, the endolymph and the perilymph, are known and well tabulated. However, data on the physical properties of interest for fluid dynamics analysis of the semicircular canals is scarce and very limited in scope. Consequently, an experimental program to measure the relevant characteristics of the fluids was outlined and the bulk of the preparatory work has been carried out. Under this program the following measurements were to be made:

a) density - ρ

b) coefficient of volume expansion - $\frac{d\rho}{dT}$

c) viscosity - μ

d) thermal coefficient of viscosity - $\frac{d\mu}{dT}$

e) thermal conductivity

Because of the necessity of performing measurements with very small samples, on the order of one microliter, standard instrumentation is inadequate. Adaptation of existing measurement techniques to the task at hand involves recalibration of instruments and construction of a precise microviscometer. The microviscometer built at the Man-Vehicle Control Laboratory was designed along the principle of the rolling ball viscometer of Flowers. The visocsity of a fluid measured with this viscometer is determined to a first order approximation by the formula

$$\mu = \frac{K}{v} [\rho_B - \rho_F] = At\ [\rho_B - \rho_F]$$

where

ρ_B = density of ball

ρ_F = density of fluid sample

v = terminal velocity of ball in the fluid

t = time for ball to travel a fixed distance

K, A = gain constants of the instrument

Also, it has been shown by Hershey that the relative error obtained by ignoring the initial acceleration to terminal velocity for fluids with a viscosity near water can be expressed by the relation

$$\frac{\Delta T}{T} = 0.21[1-(1 - \frac{1}{T_o^2})^{\frac{1}{2}}]$$

where

$$T_o = \text{total time of travel}$$

for $T_o = 10$ sec.

$$\frac{\Delta T}{T} = 0.21[0.005] \simeq 0.1\%$$

To further improve the accuracy of the measurement of the velocity of the rolling ball, in our viscometer, the velocity is measured over a small (1 cm) distance at the end of the tube and long after the terminal velocity has been reached. One further source of error arises from the variation of the gain constant of the instrument, A, with temperature. This variation, however, is taken into account by careful calibration of the instrument with known fluids at several temperatures.

Description of the Microviscometer

The basic velocity (or time) measurement unit is an epoxy block with two miniature lamps and photodiodes to measure the time of travel of a tungsten carbide sphere in a miniature pipette. A modified 5 μl lambda pipette containing the sample is mounted in such a manner that both light beams are broken by the rolling sphere and the time interval as presented by the outputs of the photodiodes are recorded by external electronic circuitry. The epoxy block is mounted on a hinged platform at an angle of twenty degrees from the horizontal and is provided with an external cable to tilt the platform to return the ball to the beginning of the tube. The inclined plane is mounted on a ten inch triangular plate which is provided with two levels and two adjustable legs for leveling and power resistors for control of fluid temperature. The sample temperature is monitored by a thermocouple mounted in the epoxy block. Open loop temperature control will be applied unless measurement accuracies require a closed loop controller. The entire apparatus is confined by a plexiglas case for temperature stabilization and cleanliness. Time measurements are made via an electronic counter to an accuracy of 10^{-6} sec.

Techniques for Handling Samples

Because of the small quantity and volatility of endolymph and perilymph extreme care must be exercised in transferring the samples into and out of the viscometer. Each 5 μl glass capillilary is sealed at one end and fitted with a tungsten carbide sphere of 0.010 in. diameter. The neck of the tube is then heated and fitted with a small stainless steel insert to prohibit the ball from leaving the tube. A 10 μl hypodermic syringe equipped with a custom designed 0.008 in. diameter is used to transfer the samples and a four step cleaning sequence (alcohol, acetone, ether, air) is used on the tubes before reloading a new sample. A small stainless steel cap with a piece of surgical steel wire is used to seal the tube to prevent evaporation, and to prevent the sphere from being caught in the surface tension of the fluid.

IV. FLUID DYNAMIC ANALYSIS OF THE CUPULAR-ENDOLYMPH SYSTEM

The dynamic response of the semicircular canals as measured by rotatory nystagmus or subjective estimation of angular velocity is in disparity with theoretical models of the canals. Approximate analytical attempts to evaluate the characteristics of the canals in terms of time constants of the transient response result in estimates of these characteristics outside the range observed experimentally. In an attempt to resolve the gap between theory and experiment in this area of vestibular research, we initiated an analytical effort to solve the Navier-Stokes equations associated with the flow of endolymph in the canals. With the knowledge of the physical properties of the labyrinthine fluids, the exact formulation of these equations is feasible.

Our research activities in the area of fluid dynamics analysis proceeds along two parallel directions. One approach considers the laminar flow of a Newtonian fluid in a solid, inflexible tube when subjected to angular accelerations. The solution of these Navier-Stokes equations, either in closed form or by successive iterations, should present an analytical transfer function of the semicircular canals relating skull rotation to cupular deflection.

The second effort attempts to analyze the fluid flow in the semicircular canals assuming a flexible wall structure. This investigation is carried out in order to determine whether linear accelerations can induce fluid rotation in a flexible tubular angular accelerometer. This is an attempt to establish analytically the sensitivity of the semicircular canals to linear accelerations based on several assumptions about canal structure.

The analytical investigation described in this section of the report is expected to be completed in the second half of 1966.

V. CALORIC STIMULATION OF THE SEMICIRCULAR CANALS

The phenomenon of caloric stimulation of the semicircular canals is well known and used extensively both in research and for clinical diagnosis. Observed nystagmus response during periods of caloric stimulation is explained in terms of convection currents which set up fluid flow in the semicircular canals. Although sufficient evidence in favor of such a "convection current" model exist, a modeling effort has not been undertaken yet.

In particular, the relation between fluid temperature input at the tympanic membrane and equivalent angular acceleration on the semicircular canals has not been evaluated.

Our research activities in the area of caloric stimulation will draw heavily upon the knowledge which we will gain from experimentation and analysis on the properties of the labyrinthine fluids and the dynamics of the fluid flow. The emphasis during the first half of 1966 has been on an effort to establish analytically the similarity between caloric stimulation of the semicircular canals and excitation with angular acceleration.

It has been clearly shown by the work of Cawthorne and Cobb that the application of a thermal input to the tympanic membrane results in a temperature gradient across the horizontal semicircular canal. This temperature gradient gives rise to a convection current of fluid in the canal and results in a nystagmus output from the subject.

The transfer function of the temperature gradient across the canal as a result of caloric stimulation has been computed by a minimum mean squared error fit of the data from the measurements of Cawthorne and Cobb to a first order dynamic lag model and the results were found to be:

$$\frac{\Delta T}{T} = \frac{k}{\tau s+1}$$

where

$k \approx 0.1$

$\tau \approx 20$ sec

$s = j\omega$

T = temperature of tympanic membrane above body temperature

ΔT = temperature gradient across canal above body temperature

To transfer the observed temperature gradient to a torque on the fluid of the semicircular canals and thus to an angular acceleration the following simplified model is proposed.

When a ring of inviscid fluid is placed in the field of a constant uniform temperature gradient, a given torque is exerted on the fluid. The same torque may be exerted by angular acceleration of the ring. The relation between this angular acceleration (α) and the corresponding externally applied temperature (T) is given by the relation

$$\alpha = \frac{1}{4R} \left(\frac{\Delta\rho}{\rho\Delta T}\right) g \frac{kT}{\tau s+1}$$

$\frac{\Delta\rho}{\rho\Delta T}$ = relative change in density with temperature

R = radius of the ring

g = acceleration of gravity

For water as a fluid and for a ring of the dimensions of the horizontal canal

$k = 0.1$

$\tau = 20$

$g = 980\ \mathrm{cm/sec}^2$

$\frac{\Delta\rho}{\rho\Delta T} = 0.4\mathrm{x}10^{-3}/\ ^{\circ}\mathrm{C}.$

$\alpha = \frac{0.0327}{20s+1}\ T$

To compare the thresholds of angular acceleration and caloric stimulation, consider a typical threshold temperature of $T = 0.2^{\circ}C$ resulting in

$\alpha = 0.374^{\circ}/\mathrm{sec}^2$

Since a typical threshold angular acceleration is of the order of $0.2^{\circ}/\mathrm{sec}^2$ the agreement is reasonable. The factor of two disparity is attributable to the computation of the gain k. The data of Cawthorne and Cobb was taken during surgery and obtained by a thermocouple inserted into one half of the horizontal canal thereby displacing about half of the endolymph in the canal. This could well result in a higher temperature gradient than actually exists. It is envisioned that the analytical model for caloric stimulation of the semicircular canals will be supported by experiments to be carried out during the second half of 1966.

VI. FUTURE PLANS

Our plans for research in the latter half of 1966 call for continuation of the programs already in progress and described in this report, and initiation of one new area mentioned in our proposal. This new area concerns Coriolis accelerations. There are many bizarre effects on the human when subjected to abnormal motion environments. Several of these effects can be attributed to Coriolis accelerations not anticipated by the human or to be due to a conflict of information in the reference frames of the vestibular sensors and the visual system. We feel that an analytical effort to establish the motion patterns causing Coriolis accelerations and the dynamics of the response are well warranted at this time.